Publisher: Engineering College, Al Muthanna University

Open Access

DOI:10.52113/3/eng/mjet/2026-14-02-/91-99, Vol. (14), Issue (2), (2026)

Muthanna Journal of Engineering and Technology

MJET

Submitted 02 February 2026, Accepted in revised form 21 April 2026, Published online 09 May 2026

Synergising AI-Driven Kinetic Façades and Machine Learning for Thermal Load Mitigation in Iraq's Administrative Infrastructure: A Predictive Simulation Approach

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Abstract

This study investigates the performance of an AI-driven kinetic façade to reduce cooling demand and improve daylight conditions in administrative office archetypes in Baghdad, Iraq, where extreme summer temperatures and frequent dust events limit the effectiveness of static envelope systems. The research addresses a regional gap in the application of predictive façade control that simultaneously responds to solar exposure, indoor daylight requirements, and dust-shielding needs. A parametric building model was developed in Rhino and Grasshopper and evaluated using Ladybug, Honeybee, and EnergyPlus-based environmental simulations with Baghdad EPW climate data. A predictive control model was trained on simulation-generated data to predict façade opening angles based on solar geometry, outdoor temperature, and operational conditions, while maintaining indoor illuminance at acceptable workstation levels. The results indicate that the proposed system reduced the cooling energy use intensity from 185 to 121.7 kWh/m²·yr, representing a 34.2% reduction, and lowered July peak cooling demand by 41%. The system also improved useful daylight illuminance from 45% to 78% of occupied hours, reduced discomfort glare by 62%, and maintained an effective solar heat gain coefficient below 0.15 during peak hours. These findings indicate that predictive kinetic façades can provide a viable envelope-level strategy for improving thermal and visual performance in hot-arid administrative buildings, provided that control logic and mechanical operation are explicitly integrated into the evaluation framework.

Keywords: *AI-Driven Kinetic Facade; Dust Shielding; Energy Use Intensity (EUI); Machine Learning (ML) Model; Predictive Simulation.*

1. Introduction

The global construction sector is undergoing a paradigm shift towards greener methods due to growing environmental and sustainability concerns. The construction and building industry is a major consumer of natural resources and a major global carbon emitter. Therefore, a sustainable architectural and structural solution should be provided in order to mitigate the damage. Buildings that incorporate sustainability into their design and materials, as well as long-term viability, reduce their carbon footprint and enhance the efficiency of the resources they use. [1,2].

In places where climatic conditions are much harsher, such as Iraq, the problems are very grave. Mechanical cooling (HVAC) systems are overloaded due to high thermal gains caused by summer temperatures above 50°C in various commercial and administrative buildings. The energy uses of sustainable strategies, including passive design, high-performance insulation, and energy-efficient glazing, have been proven to mitigate. Static solutions cannot adapt to the rapidly changing state of solar angles or dust storms, which can suddenly pour into the urban fabric of Iraq's desert [3,4].

To overcome these limitations, the research proposes AI-Driven Kinetic Façades. Kinetic façades are movable building envelopes that change their shape to better respond to the environment. Through Machine Learning (ML), these Façades are now capable not only of reacting but also of forecasting. The shade elements of a machine-learning-powered façade are adaptively varied based on past weather data and anticipated solar input. It doesn't just react to the current sensor input. [5,6].

The central aim of this research is to connect architectural design with advanced computational intelligence. This research assesses whether predictive AI control can enhance the performance of envelope enclosures in Baghdad's public administrative buildings by mitigating cooling demand, managing solar gain, and sustaining useful daylight indoors under hot-arid, dust-storm-prone conditions.

The solution permits digital transformation and ensures sustainable institutional development in the region in a scalable manner.

Although research on adaptive façades and AI-assisted building control is increasing, three gaps have not yet been addressed in Iraq. Many studies focus only on thermal or daylight performance, without integrating both in a single façade-control system. Kinetic façade studies in hot-arid regions have rarely considered dust events as operational design variables. Research limited to machine-learning-based predictive façade control has likewise been done for the administrative buildings in Baghdad, with peak summer heat-dust and airborne dust causing combined stress on façades. As such, this study aimed to develop and evaluate an AI-powered kinetic façade model for an administrative building in Baghdad using a single predictive simulation that integrates logic for solar control, daylight sufficiency, and dust shielding. This study offers a control strategy tailored to the specific needs of this region. It compares the performance of baseline and proposed façade conditions. It provides a methodological framework that links parametric modelling, environmental simulation, and a machine-learning-based decision-making algorithm.

2. Literature Review

The shift from static to adaptive building-envelope systems is now a key concern in sustainable architecture, especially in regions with cooling-driven operational energy requirements. To achieve façade performance in hot-arid climates, aesthetic and passive insulation alone are not sufficient; solar gain, daylight access, glare risk, indoor comfort, etc., must also be taken into account. Subsequent research focused on kinetic and responsive façades, performance-oriented systems capable of adapting to changing environmental conditions. The literature has been reported as disconnected and piecemeal, with envelope behaviour examined in only one study at a time. For the purpose of the study, four interrelated aspects will be examined through the review: kinetic façades in hot-arid climates, AI-based predictive control, daylight-thermal trade-offs, and dust-related envelope response in arid areas.

2.1. Adaptive and Kinetic Façades in Hot-Arid Climates

Adaptive and kinetic façades have been widely recognized as sophisticated alternatives to static envelope systems for coping with high-solar-gain climates. Kinetic 'Facades' are design elements that are not fixed zoning devices but are within the possibility to change geometry, open state, and/or orientation in response to variable prevailing conditions. They may limit heat absorption during peak hours, but still react to their environment at other times. Research from hot-arid climates suggests that the application of these systems improves façade performance by mitigating direct radiation and minimizing the need for conventional cooling techniques. This is particularly applicable to office buildings that have large glazed areas. In such buildings, solar exposure contributes significantly to cooling loads and occupant discomfort [7].

In desert and semi-desert environments, energy and shading greatly benefit responsive façades. Architecture projects such as Al Bahar Towers are often cited as case studies for climate-responsive envelope design, whereby movable external shading can mitigate solar gains and enhance façade performance. However, much research still centers on geometric adaptation and shading effectiveness. Most research treats the facade primarily as a thermal-control component. Integrated performance outcomes that mitigate cooling and provide sufficient daylight are less well addressed. They do not deal with site-related ecological constraints with regional outcomes. Consequently, adaptive façades, while theoretically well-established, are not yet in use in Iraqi governmental building construction in a methodological and contextual sense [7].

2.2. AI and Predictive Control in Façade Optimization

There is a growing trend in research towards predictive optimization rather than just reactive control in the context of artificial intelligence applications for façade systems. In the past, automatic façades operated according to predetermined cycles or were activated by direct sensors. In contrast, recent research increasingly uses predictions of environmental change generated by machine learning and decision-making before events. To estimate thermal behaviour, predict façade states, and optimise visual and environmental performance under variable climate conditions. AI-based approaches include Artificial Neural Networks, various gradient-boosting models, and reinforcement learning [8].

The two weaknesses still observed in the literature, notwithstanding more progress. Many facade studies powered by AI are conducted in advanced countries outside Iraq, without regard for Baghdad's climate and infrastructure. Many of these studies on glare reduction, thermal comfort, energy efficiency, and related topics consider only one target variable at a time and do not combine them within the control logic used for predictions. As a result, there is still a need for studies that employ AI as an operational control layer, rather than just as a computing add-on, to balance multiple façade-related performance objectives in hot-arid regional conditions [8].

2.3. Daylight–Thermal Trade-off in Responsive Envelopes

One of the primary difficulties in façade design is balancing solar heat gain reduction with adequate daylighting. Over-shading could lower cooling demand but would also cut daylight availability and raise artificial lighting demand. On the other hand, increasing transparency or opening the façade may increase daylight penetration but increase cooling loads and risk of glare. In office buildings, it is critical that façades perform to support heat retention and visual requirements during occupied working hours [9].

Responsive façades are often presented as a solution to this conflict, as they can respond over time to both solar position and internal comfort needs. However, not all the responsive systems meet the conflicting demands. Daylight and thermal metrics are often reported separately in many published studies, rather than as simultaneous control constraints. Therefore, the practical relevance of the results is weakened, as real façade operations must meet both conditions. To ensure that useful daylight levels are maintained when controlling glare, and the daylighting levels that maximise solar gain should not be allowed. This perspective is important for intelligent façades optimized for office use that receive high levels of solar radiation [9].

2.4. Dust Events and Envelope Performance in Arid Regions

In hotter, drier regions, heat and sunlight are not the only factors; dust storms in the atmosphere also affect the façade. Dust storms can reduce visibility outdoors, degrade indoor air quality through infiltration, and reduce the efficiency of façade systems, requiring increased maintenance of mechanical and envelope systems. Nonetheless, the building envelope's response to particulate exposure has not yet been fully addressed in the façade literature, which has arguably been more concerned with thermal gain, daylighting, and energy demand.

The absence of this information matters for understanding Iraq's dust storms. Dust storms in Iraq are not one-time events but happen regularly. This has an impact on buildings. A façade system intended for Baghdad should therefore respond not only to solar geometry and temperature but also to dust-related risk. The inclusion of a dust-shielding mode represents an important extension of the adaptive façade concept, expanding the envelope's role from energy moderation to broader environmental protection. Accordingly, dust should be treated as an operational variable in façade-control design rather than as a secondary contextual remark.

2.5. Research Gap and Study Positioning

Research indicates that employing kinetic façades will improve shading performance and reduce cooling loads in hot climates. On the other hand, predictive control for adaptive envelope systems is possible, according to recent AI studies. In yet another study, the authors noted that no integrated strategy in the literature currently combines thermal control, daylight adequacy, and dust-event response into a single predictive façade for Iraqi administrative buildings. Many published studies either focus solely on solar and glare control or address adaptive façades in other regional contexts, such as the UAE, Saudi Arabia, etc. The current research merges three dimensions that have not been addressed in predictive control based on machine learning and in the solar–daylight–dust response applied to the hot-arid administrative building typology of Baghdad.

3. Conceptual Framework

The conceptual framework assumes that the façade's movement is influenced by environmental inputs and operational conditions via a predictive control layer. The predictive control model generates the optimal opening angle of the kinetic modules in real time or in simulation based on environmental variables. The selected angle is then assessed using three performance objectives: reducing cooling demand, maximizing the useful daylight, and activating dust-shielding mode during high-PM10 conditions. This framework clarifies how climate effects drive façade control actions, which, in turn, lead to building performance outcomes.

Table 1. Conceptual framework of variables and control logic

Variable group	Variables	Role in model	Output relationship
Independent variables	Solar azimuth, solar altitude, outdoor dry-bulb temperature, PM10 concentration, grid load	Environmental and operational inputs	Affect façade decision logic
Control variables	Façade opening angle, panel rotation state, façade coverage ratio, control schedule	Adjustable design/control parameters	Mediate envelope response
Dependent variables	Cooling EUI, peak cooling load, UDI, glare, SHGC, PMV, dust protection efficiency	Performance outputs	Used to evaluate effectiveness

4. Methods and Materials

This research presents a mixed-methods computational approach that employs Building Information Modelling (BIM) and parametric environmental simulation to develop an intelligent building envelope with Machine Learning (ML) modelling parameters. The objective of the method described herein is to yield results accurate enough for direct application in Iraqi construction.

4.1. Case Study Definition and Archetype Selection

The study relies on a typical administrative office building model common to the public-sector mid-rise typology in Baghdad, rather than a specific building. The archetype was defined using typical geometric characteristics, envelope performance, and occupancy characteristics observed in buildings in Baghdad, including an administrative building with a reinforced-concrete frame, glazed curtain-wall sections, regular daytime occupancy, and high solar exposure on its south and west façades. This methodology was adopted to test the façade-control approach under relevant climatic and operational conditions while providing parametric flexibility for simulation.

Even though there are limitations in controlling the contextual relevance of the archetype model, it does enable a controlled evaluation of the façade performance in Baghdad's climate by maintaining the geometric and operational assumptions transparent. As a result, all reported findings refer to the baseline archetype model and the proposed AI-driven kinetic facade model derived from it. The estimates should not be interpreted as measured values of a real building.

Table 2. Baseline archetype characteristics before simulation

Parameter	Value
Model type	Archetype administrative office model
Context	Baghdad, Iraq
Climate type	Hot-arid
Building function	Administrative office
Building typology	Mid-rise public-sector office
Structural system	Reinforced-concrete frame
Envelope condition	Baseline glazed curtain-wall configuration
Occupancy pattern	Regular daytime office occupancy
Target façades	South and west
Model purpose	Representative simulation model for façade-performance evaluation

Note: The table values display the simulation archetype used in the present paper rather than a named administrative building. An archetype was defined to characterize the geometric and operational similarities among the Baghdad office buildings for comparative simulation.

4.2. Digital Workflow

The computational workflow can be dissected into five steps: (1) creating the baseline archetype geometry within Revit and importing to Rhino; (2) generating a library of parametric façade modules in Grasshopper; (3) conducting climate-based environmental simulation using Ladybug and Honeybee with the EPW data for Baghdad; (4) extracting simulation outputs to generate the predictive-control dataset; and (5) evaluating façade-opening decisions against the baseline and proposed simulation conditions.

4.3. Parametric Façade Geometry

The kinetic façade put forth consists of modular origami-shaped shading units mounted on the glazed façade zones of the archetype building, rather than on the opaque wall zones. All units were simulated as a foldable panel assembly with an opening angle ranging from 0° (fully closed) to 90° (fully open), corresponding to 0%–100% operational openness. The modules were replicated across the target façade grid, following the glazing spacing of the existing curtain wall. The parametric model enabled adjustment of panel dimensions, rotation angle, spacing, and façade coverage ratio to test different operational states under changing solar and environmental conditions.

Table 3. Kinetic façade module specifications

Parameter	Value
Module geometry	Origami-inspired foldable panel
Opening angle range	0°–90°
Operational openness	0%–100%

Motion type	Rotational/hinged
Application zone	Glazed façade sections only
Target orientations	South and west

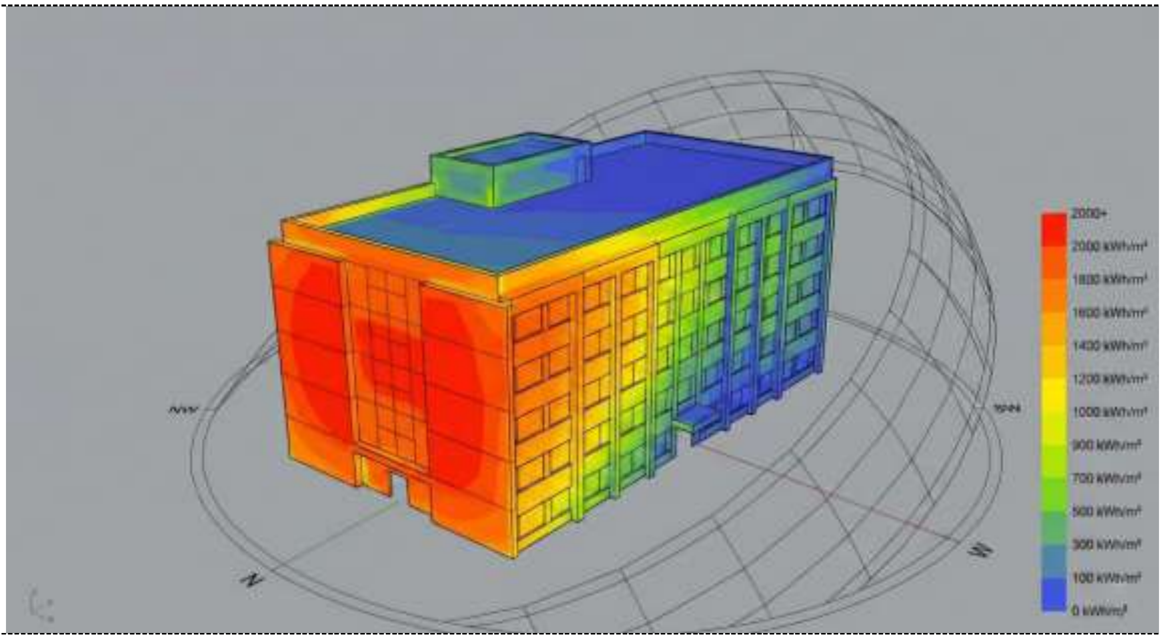
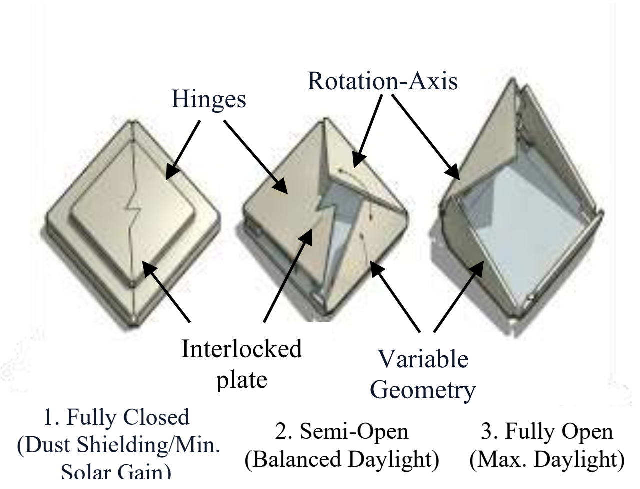


Fig. 1: Annual solar-radiation distribution on the baseline archetype administrative office model in Baghdad.

Figure 1 presents the annual solar-radiation analysis of the baseline archetype model using Ladybug and Honeybee in Rhino/Grasshopper with Baghdad EPW climate data. The radiation map indicates that the south and west façades receive the highest levels of solar exposure, which justifies prioritizing these elevations in the façade-control analysis. This distribution also explains the concentration of thermal loads on the most exposed glazed surfaces of the archetype model.

(a): Baseline Façade (No Kinetic Modules).

(b): Proposed Kinetic Façade (Variable Opening States)



(c): Module Folding Logic Close-up

(d): Simple rectangular concrete-and-glass office block representing a typical non-iconic public-sector archetype

	in Baghdad, characterized by large glazed curtain walls.

Fig. 2: Parametric kinetic façade model developed in Rhino/Grasshopper and applied to the glazed sections of the baseline archetype model.

Figure 2 illustrates the proposed origami-inspired kinetic façade, generated in Rhino and Grasshopper, applied to the glazed façade zones of the baseline administrative office archetype. The modules were designed to switch between closed and open states under predictive control in response to environmental inputs. The purpose of this system is to reduce solar gain, preserve useful daylight, and activate a shielding response during high-dust events within the simulation framework.

4.4. Environmental Simulation Setup

Environmental simulations were conducted using Ladybug and Honeybee with Baghdad EPW climate data. The baseline archetype model and the proposed AI-driven kinetic façade model were tested under identical occupancy schedules, internal-load assumptions, and envelope conditions to isolate the performance effect of the kinetic façade. The annual solar irradiation, air conditioning energy demand, peak cooling load, useful daylight illuminance, and glare daylight performance were simulated for the occupied office zones. The south and west façades were analysed because the first solar-radiation analysis showed the highest values at these areas.

A shielding mode was embedded into the simulation logic for dust-event response once the PM10 concentration exceeded 200 µg/m³. The limit was treated as an operational parameter in the control framework rather than as a measured field value from a given real building.

4.5. Predictive Control Model Development

A model-predictive control system for the facade was developed based on simulation data. The model uses environmental input variables, solar azimuth, solar altitude, outdoor dry-bulb temperature, PM10 status, and operational load condition for the estimation of façade opening angle, which would help in the reduction of solar gain while maintaining an acceptable daylight level in occupied office zones. Various climatic and operational scenarios were represented through 5000 parametric simulation iterations for the data set. The current modeling process defines a predictive control layer that connects environmental inputs to façade-response decision-making processes. Due to the lack of documentation for the detailed training architecture and hyperparameter settings in the current version of the workflow, these are not presented as fixed parameters for the predictive control model.

4.6. Façade Control Objective

The control objective of the proposed system was not to maximize shading at all times, but rather to find a façade opening state that minimizes both the building's cooling demand and glare, while maintaining indoor daylight within an acceptable useful range. The logic of facade-control, applied at the operational level, sought to reduce solar heat gain while maintaining indoor illuminance above 300 lux in occupied work places. This multi-criteria logic was essential because reducing heat and having adequate daylight do not always support each other. The balancing of these then needed to happen through controlled movement of the façade.

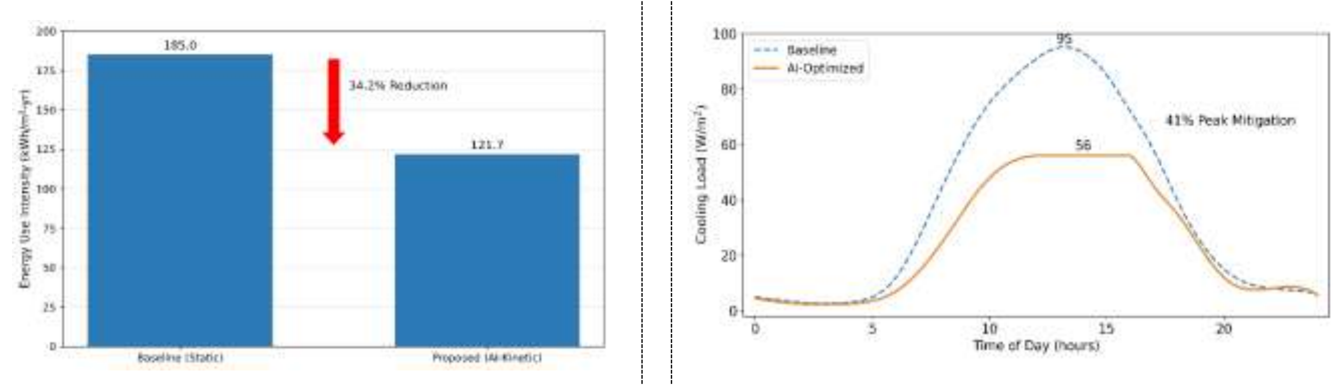
4.7. Performance Evaluation Method

The assessment of the proposed system was conducted based on the cooling energy use intensity (EUI), peak cooling load, useful daylight illuminance (UDI), solar heat gain coefficient (SHGC), and the glare-related daylight performance indicator. The cooled energy use intensity was computed as the annual cooling-energy requirement divided by the conditioned floor area. The hourly simulation results from the hottest month, July, were used to determine the peak cooling load. UDI denotes the percentage of occupied hours when the indoor illuminance was in the useful daylight range, that is, 300–2000 lux. A comparative evaluation of glare risk performance was undertaken between the baseline and proposed façade cases. The operational definition of dust-protection performance was the percentage of dust-event hours during which the façade entered shielding mode (PM10 > 200 µg/m³).

5. Results

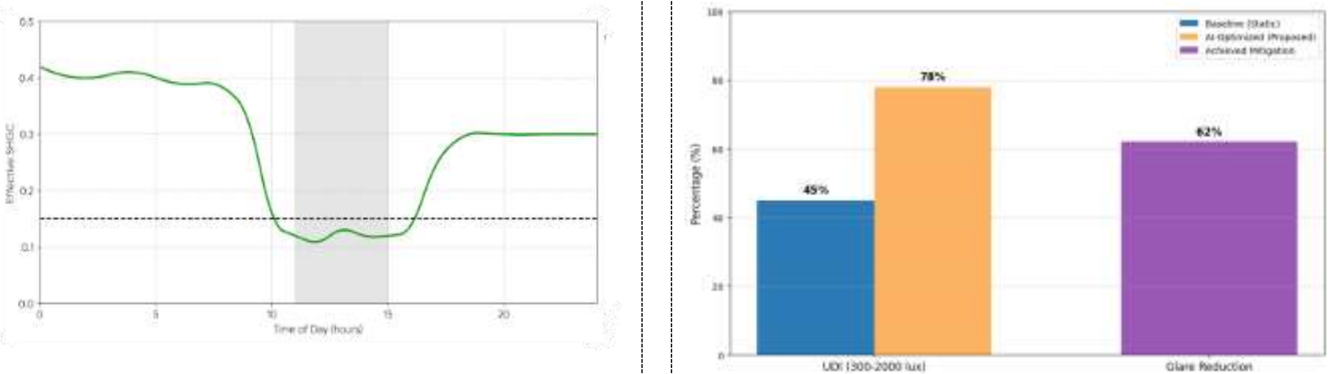
5.1. Overall Comparative Performance

The performances of the baseline Baghdad administrative office archetype aided in the final simulation exercise to measure the efficiency and effectiveness of the proposed AI-driven kinetic façade model in comparison. Figure 3 depicts the comparative behavior of the baseline and the proposed model under the same weather and work conditions.



Graph (a): Annual Cooling Load Comparison.

Graph (b): Peak Summer Day Cooling Demand Profile (July).



Graph (c): Dynamic Solar Heat Gain Coefficient (SHGC)

Graph (d): Daylight & Glare Performance

Fig. 3: Comparative performance of the baseline archetype model and the proposed AI-driven kinetic façade model.

Figure 3 summarizes the simulation outputs generated through Python, Scikit-learn, and Matplotlib for the baseline archetype model and the proposed AI-driven kinetic façade model. The proposed system reduced the cooling EUI from 185 to 121.7 kWh/m²·yr, a 34.2% reduction. July peak cooling load decreased by 41%, useful daylight illuminance improved from 45% to 78% of occupied hours, and glare-related conditions were reduced by 62%. In addition, the effective SHGC remained below 0.15 during peak hours under the proposed façade-control regime.

5.2. Energy Consumption and Thermal Load

The baseline archetype model recorded cooling energy use intensity (EUI) 185 kWh/m²·yr, while the proposed AI-driven kinetic façade model reduced this to 121.7 kWh/m²·yr, 34.2% due to a reduction in energy use intensity (EUI). Based on the findings, integrating predictive control into façades can dramatically reduce the annual cooling load in Baghdad's hot-arid climate.

The July peak cooling load in the baseline case is 95 W/m², whereas it is 56 W/m² in the proposed case, a difference of 41%. The kinetic façade can minimize short-term thermal stress in peak summer times due to this reduction.

In other words, during peak solar exposure between 11 AM and 3 PM, the proposed façade achieves an SHGC of less than 0.15. With this result, the adaptive opening state of the modules proved to be effective at controlling direct solar gains on the most exposed glazed surfaces.

5.3. Lighting and Visual Comfort

In contrast to shading systems that remain static, the proposed AI-controlled façade was designed to maintain useful daylight in the space while minimizing excessive solar penetration. The baseline archetype model has useful daylight illuminance for 45 % of occupied hours, while the proposed façade has 78 %. This means that the adaptive control strategy increased daylight availability without requiring a permanently open facade.

In comparison to baseline cases, the proposed control strategy reduced glare conditions by 62%. This result suggests that façades capable of predicting the angle of sun-fall can effectively prevent direct solar access to the occupied zone of an office, while maintaining acceptable illumination levels.

5.4. Performance Metrics Comparison

The table below illustrates the contrasting performances of traditional structural solutions and the structural solutions of the intelligent architecture employed:

Table 4. Comparative performance of the baseline archetype model and the proposed AI-driven kinetic façade model

Metric	Baseline	Proposed	Difference	Improvement
Cooling EUI (kWh/m²·yr)	185	121.7	-63.3	34.2% reduction
Peak cooling load (W/m²)	95	56	-39	41.0% reduction
UDI (% occupied hours)	45	78	+33	73.3% relative increase
Dust-shielding response	Passive	Active	—	Triggered at PM10 > 200 µg/m³

Note: All values reported in this table were obtained from comparative simulations between the baseline archetype model and the proposed AI-driven kinetic façade model under identical climatic and operational assumptions. The performance metrics should be seen as derived from simulations, not as actual field results from a lone building.

In addition to the results presented in the table, the control strategy proposed achieved a 62% glare reduction compared to the non-optimized model, and the effective SHGC is below 0.15 during peak hours.

6. Discussion

The proposed AI-driven kinetic façade improved thermal and visual performance compared to the baseline archetype model in Baghdad under its climatic conditions. According to a previous study on AI-assisted optimization of facades and machine-learned kinetic control systems [5,6], reductions in cooling EUI and peak cooling load indicate that predictive facade control can outperform static envelope behaviour during highly solar-exposed periods. The rise in useful daylight illuminance confirms that we efficiently managed thermal comfort without reducing daylight availability inside the building. This is particularly important in hot-arid office buildings because excessive shading may lessen cooling loads but may also compromise indoor daylight performance when not controlled [7,9].

The second major implication of the findings concerns the incorporation of dust response into the façade-control framework. In this study, dust was treated as an operational variable rather than merely a contextual background variable. This expands the façade's function beyond solar mitigation to encompass overall environmental protection under the Iraqi climate. The facade was therefore conceived in the simulation logic not merely as a moving shading screen, but as a responding environmental filter. This analysis is supported by earlier work demonstrating that, through intermittent heating and cooling, regionally based environmental pressures in Iraq made adaptive envelope behaviour important [4].

The results still need to be seen in the context of a simulation study using archetypes. Given that the present research is not assessing a single named administrative building, the outcomes should be viewed as evidence of performance potential rather than field-validated retrofit outcomes. The archetype approach is still beneficial for testing methods and for comparatively assessing performance, but it is not a substitute for building real ones.

There are three limitations of this study. First, physical validation at prototype or pilot scale is required, because the façade-control strategy was evaluated in a simulation environment. The present analysis focuses primarily on cooling energy and daylight outcomes; thus, net energy performance should be interpreted with caution unless façade-actuation energy is explicitly included. Moreover, further research is required on the durability and maintenance needs of moving facade modules in high-dust environments.

Carbon emissions cuts and water-use reductions for cooling may be other potential environmental impacts. However, these impacts require assumptions to be calculated and are therefore not validated here as primary impacts. In broader terms, this interpretation aligns with earlier studies that found that AI-assisted management of building systems improved environmental performance and optimized energy use [10].

7. Conclusion

An AI-driven kinetic façade was studied to enhance the envelope's performance in an administrative office archetype in Baghdad's hot-arid climate. The simulation results showed that both cooling demand and peak cooling load were reduced significantly, along with improved daylighting performance and controlled solar gain during high-exposure times. The key contribution of this study is to implement a machine-learning-based predictive control strategy, combined with a thermal–daylight–dust response, in a simulation-based framework appropriate for Iraq.

Because the model is based on an archetype rather than a single building with a name, the findings should be interpreted as evidence of comparative performance potential, not as field-validated results of a retrofit. Future research should extend the current framework to actual construction applications, to actuator energy accounting, and to durability assessment under long-term recycled-dust exposure. The proposed approach provides a systematic framework for evaluating intelligent, responsive façades in administrative office typologies that are subject to extreme climatic conditions.

Acknowledgement

I want to thank my colleagues, friends, and family for their support and encouragement throughout this work.

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Image Sources:

- Solar Radiation Analysis Diagram: Generated via Ladybug Tools for Grasshopper/Rhino 7 (Figure 1).
- Author-generated using Rhino/Grasshopper. (Figure 2).
- ML Performance Graphs: Python Scikit-learn Matplotlib outputs for predictive thermal load analysis (2025) (Figure 3).